6. Electricity & Magnetism

updated 14 March 2004

Take two electrons and place them a centimeter from each other. Make sure nothing else is around. The force of gravity will attract them to each other. But, for the two electrons, there is another force, something we call the "electric" force. The electric force between these two electrons is stronger than the gravitational force by a factor of approximately:

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I wrote it that way to be dramatic; the same number can be written as 4.17×10^{42}. Moreover, this electric force is repulsive. It pushes the two electrons apart. It completely overwhelms gravity.

Now replace one of the electrons with a proton. Now the two particles, the electron and the proton, will attract each other, not repel. Moreover, the electric force of attraction will be exactly the same as the prior force of repulsion.

In a hydrogen atom, the electron manages to overcome this huge attraction by its centrifugal force as it orbits the proton. To do that requires great speed. The velocity of the electron in the hydrogen atom is approximately 2×10^8 cm/sec = 1/137 of the speed of light. And remember, the centrifugal force depends on the square of this velocity. That is what is needed to overcome the strong electric attraction.

Here is the great irony. Once the hydrogen atom is formed, the electron and the proton are so close to each other, that other particles (such as you and me) hardly feel any force at all. An electron passing by the hydrogen atom feels a repulsion from the electron in the atom, and an attraction from the proton, and these two forces cancel. So it feels virtually no net force whatsoever. Most of the electricity is hidden inside the atom.

But when it gets out, it shows its enormous strength, a strength that can be frightening, and enormously useful. Electricity is the heart of the lightning bolt, and of the delicate calculations done within a computer. Electricity is used for radio communication, and to send telephone signals through wires. Electricity is the most convenient (if not always the cheapest) way to transport energy. It comes into our homes when needed by the flick of a switch, through nationwide circuitry some complex that it can collapse in a few seconds. It is so safe that we have outlets all over our homes, and yet it is still used as a gruesome method of execution.

Electric charge

The property of the electron that lets it participate in the electric force is given a name. We call it the electric "charge." By convention, the charge of the proton is $q_p = 1.6 \times 10^{-19}$ Coulombs. You won't need to know that number. The charge on the electron is $q_e = 1.6 \times 10^{-19}$. We believe that these numbers are exactly equal in magnitude and opposite in sign, i.e. that $q_e = -q_p$. The opposite sign is why their force cancels when the two are combined.

Neutrons don't "feel" electric forces. Another way to say that is that the charge of a neutron is zero: $q_n = 0$. That's where it got its name; it is neither positive nor negative, but neutral.

What about inside the neutron? Is it neutral only because its pieces cancel, just like a hydrogen atom (consisting of a proton and electron) is neutral? The answer is yes. A neutron is believed to consists of three quarks: u d d. The charge of the u quark is $+2/3\ q_p$ and the charge of each d quark is $-1/3\ q_p$. So the net charge is zero. That's why the neutron is neutral. The proton consists of u u d, with a total charge of $+1\ q_p$.

As far as we know, all charges in nature are exact multiples of the quark charge. It also appears that all "free" charge (charge not hidden inside a nucleus) comes in multiples of the electron charge. We don't know the reasons for these laws, but they have been tested to very high accuracy.

Electric current

When charged particles move, we call it electric current, in analogy to water current. Lightning is the most dramatic show of electron flow. We described it in Chapter 4 as an avalanche of electrons. Electricity can also move through a vacuum. Such flow was discovered in the 1800s, before the electron was discovered, and was called "cathode rays" (as we discussed in Chapter 4). The name endures primarily in "cathode ray tubes" or CRTs, the big bulky picture tubes still used for most television screens, and also for many computer screens.

Electricity became very important, in large part, because it not only flows through air and through vacuum, but also through metals. Wires can be thought of as pipes for electrons. When they flow through wires, the electrons collide with some of the wire atoms. The electron loses some of its energy, and the wire gets hotter. Some materials show more of this "resistance" than do others. You can use copper or aluminum wires to bring electricity into your home, with little energy lost, and then you direct that electricity into the tungsten wire of a light bulb. The tungsten has so much greater resistance, that it gets very hot. The glow from this heat is what creates the light.

About a hundred years ago (1908), Kamerling Onnes discovered a remarkable thing. If some metals were cooled close to absolute zero, their resistance would disappear completely. You could make a circular ring of metal wire, start electrons flowing, and the would flow forever. He called this phenomenon "superconductivity." The only reason we don't use superconductors in our everyday lives, is that it happens only at very cold temperatures. Many people are searching for "room temperature" superconductors, and whoever finds one may revolutionize the way we use electricity.

Material that don't conduct electricity very well (such as plastics, rocks, wood) are called insulators. But in between metals and insulators is a group of mysterious materials called "semiconductors." These are materials that can be made to turn from conductors to insulators and back, by applying electricity in a special way. Semiconductors are at the heart of transistors, computers, integrated circuits, and most of the electronic revolution.

Amps

When electrons are flowing through a light bulb, the typical number that go through the filament is about 6×10^{18} per second. (That may seem like a big number, but it really reflects how tiny an individual electron is.) This number is called an Ampere, named after one of the pioneers of electricity.[1] It is often abbreviated as an "amp." You don't have to memorize this value, but here it is in case you want to find it easily:

$$1 \text{ Ampere} = 1 \text{ amp} = 6 \times 10^{18} \text{ electrons per second}$$

The heating of a wire depends on the current. As mentioned above, a current of 1 amp is enough to heat a tungsten filament. The wires in your house can carry about 15 amps without getting too hot, and most houses have fuses or circuit-breakers that will cut off the electric flow if it ever gets higher than 15 amps.

It is interesting that a flashlight bulb, which is much dimmer than a light bulb, still carries about one amp of current. The difference is in the energy of the electrons. A bright light bulb carries its 1 amp through a long tungsten filament, and that takes very energetic electrons. In a flashlight, the filament is short, and can be heated with relatively low energy electrons. We measure electron energy with a unit called the "volt."

Here is an interesting coincidence. Suppose you let one ampere flow for a day. How many electrons total were there? One amp is 6×10^{18} electrons per second, and there are 86400 seconds per day.[2] The total number is the product of these two numbers: $6 \times 10^{18} \times 86400 = 5 \times 10^{23}$. That's almost one mole, the number of electrons in one gram of hydrogen. Think of it in the following way: if you were to take a gram of hydrogen, and remove the electrons, you would have enough to make a flow of one ampere for one day.

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[1] You might notice that this many electrons, if you add all the charge together, gives a total charge of 1 Coulomb per second. That's not a coincidence. That's how Coulombs were originally defined.

[2] 60 seconds per minute, 60 minutes per hour, 24 hours per day, gives 60x60x24 = 86400 seconds per day. Multiply this by 365 days per year to get 3.15E7 seconds per year.

Volts

If an electron has an energy of 1.6 x10^{-19} joules, we say its energy is one electron volt, often abbreviated as 1 eV. (Volt was named after another electricity pioneer, Volta, so the word volt is sometimes capitalized.) If a piece of metal has a large number of electrons at energy of 1 eV, we say that the metal is at one volt. Of course, the total energy depends on the number of electrons.

If you have a "mole" of electrons (that means 6x10^{23} electrons, the number you would have from one gram of hydrogen), then we can calculate that the total energy of this many electrons, with 1 eV each, is 23 Calories.[3] In fact, the chemical energy in one gram of hydrogen (Table 1.2) is 26 Calories, very close to this. In other words, the energy available from hydrogen gas is approximately 1 electron volt per molecule.

The chemical reactions that take place in a battery typically release electrons with an energy of 1.5 volts, or 4 volts, or something in that range. It is the energy per electron released in the chemical reaction of batteries that sets the voltage of a battery.[4]

Low voltage electrons are not very dangerous. You can hold a the flashlight battery in your hand with no danger; it typically produces electrons at 1.5 volts. (You can read that on the battery label.)

The electricity in your home is about 110 volts. That is dangerous. In Europe, household electricity is typically 220 volts, and that is potentially even more dangerous. (They use this higher voltage to reduce heating in their house wires; we'll discuss this later.) In a TV that uses a picture tube (a CRT), the electrons are given a voltage of about 50,000 volts. That can be very dangerous. Normally there is an "interlock" that turns off all the voltage whenever anyone opens the back of such a TV.

finger sparks

High voltage isn't always dangerous. When you put your hand to a doorknob, and a spark jumps to it, the voltage was probably between 40,000 and 100,000 volts. Yet it doesn't kill you. That's because voltage tells you how much energy each electron has, but to do damage, there have to be a lot of such electrons. That brings us to the topic of electric power.

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[3] 6x10^{23} electrons, each with 1.6 x10^{-19} joules, gives a total energy of (6x10^{23})x(1.6 x10^{-19}) = 9.6 x10^{4} joule. Divide by 4200 joules per Calorie, to get 23 Calories.

[4] Voltages can be made higher by putting multiple batteries together in a "series" combination (one after the other). For example, two 1.5 batteries, put together in a flashlight, can give electrons with energy of 3.0 volts.

Electric Power

Notice the following fact: if you have a current of 1 amp, with electrons at 1 volt, then the total power carried is (1.6×10^{-19} joules per electron) times (6×10^{18} electrons per second) = $(1.6 \times 10^{-19}) \times (6 \times 10^{18}) \approx 1$ joule per second = 1 watt. That's not a coincidence. The numbers were chosen to make this work out exactly.[5] So here is the important conclusion:
Power = Volts x Amps

If you have a light bulb that uses 110 volts, and carries a current of 1 amp, then the power is 110x1 = 110 watts. If you run that bulb for an hour, you use a total energy of 110 watt-hours.

back to finger sparks

The sparks that sometimes fly from your finger to a doorknob are often called "static electricity." It occurs because your feet rubbed on the ground in such a way that electrons came off and stuck to your body. These electrons are static in the sense that they stay there, on your body, until you walk up to a good conductor like a metal doorknob. You'll pick up even more electrons if you rub your shoe on a thick carpet. You can also rub electrons off a comb by running the comb through your hair. Try doing that – run the comb through several times quickly, and then put the comb near some very small (mm size) pieces of paper. The electrons on the comb will attract the bits of paper.

If the air is moist, the static electricity leaks off your body into the air. But on a very low humidity day (which means there is little moisture in the air) the air is a poor conductor, and the electrons stay on your body. They can move around inside your body, since your salty blood is a pretty good conductor of electricity. But when you have these excess electrons, and you put your finger near a piece of metal, they will jump off, creating the flow of current we call a spark.

I mentioned earlier that the energy of such electrons can be 40,000 volts or more. But there aren't usually very many of these excess electrons on your body, typically not much more than about 10^{12} of them.[6] That may seem big, but it is much less than a mole. (I am not counting the electrons in the atoms – those electrons whose electricity is cancelled by positive charge. I am counting only the excess electrons, the ones placed on your

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[5] The energy in 1 eV is not exactly 1.6×10^{-19} joules. A more accurate number is that 1 eV $\approx 1.60217733 \times 10^{-19}$ joules. An ampere is not exactly 6×10^{18} electrons per second. A more accurate number is 1 amp $\approx 6.2415064 \times 10^{18}$ electrons per second.

[6] For those of you who have studied electrical engineering, here is the way I did the calculation. I assumed the electrons had an energy of V = 40,000 eV. I assume that the capacitance of your hand was about C = 10 picofarads. Then the charge in Coulombs is Q = CV. Divide by 1.6×10^{-19} to get the number of electrons. The energy in Joules is $E = 1/2\ C\ V^2$.

body by friction with the floor as you walked over to the doorknob.) In fact, if those electrons flowed out of at the rate of 1 milliamp (i.e. one thousandth of an amp, one thousandth of the current you get in a light bulb), you would run out of electrons in only 1/1000 of a second. The total energy of the electrons is 0.01 joules, less than 2 microCalories (2 millionths of a Calorie). It is not important that you know these numbers. It is important for you to know that high voltage is not dangerous if there isn't much current.

In contrast to the little finger spark, lightning has both high voltage (millions of volts) and high current (from several thousand to several hundred thousand amps). That's why lightning is dangerous.

Sparks and the Frankenstein monster

In 1786, Luigi Galvani, one of the pioneers of electricity, discovered that static electricity when applied to the legs of dead frogs would make them twitch. Later, he hung frog legs on metal hooks outside his house during thunderstorms. (Electrical research was not easy, at least not until he invented the battery.) He thought he had discovered animal electricity. It was widely thought, at the time, that he had made the leg come alive, and that electricity was somehow the secret of life. We now know that he had discovered only that electrical impulses play an important role in the transmission of signals by nerve cells. For some fascinating drawings of his experiments, see http://www.chem.uidaho.edu/~honors/galvani.html.

Mary Shelley took Galvani's experiment, gave it a plausible extension, and created one of the first science fiction classics, "Frankenstein."

Amp-hours and Watt-hours

Expensive batteries often have numbers on them that describe how much electricity they can deliver. A battery that can deliver one ampere for one hour is said to have a capacity of one amp-hour. That is a typical specification for a "D cell" battery, the kind of battery that is typically used in a flashlight. Sometimes they will specify the capacity in milli-amp hours. A milliamp (abbreviated 1 ma) is 1/1000 amp. So a battery with a capacity of 1000 ma-hr has a capacity of 1 amp-hr.

Some batteries specify instead the energy stored in a battery. That's not given in amp-hours, but in watt-hours, or in milliwatt-hours (abbreviated mWhr). If you have an expensive battery, on a computer, digital camera, or other device, look at it and see what it says. Some batteries give you the number of mAhr (milliamp-hours), and others give you the number of mWhr. They are not the same! Since a watt is a volt times an amp, and since a milliwatt is a volt time a milliamp, we can convert from one to the other by the following simple rule:

$$\text{mWhr} = \text{mAhr} \times \text{volts}$$

This rule can be important when picking a battery. I have a camera battery that says it operates at 4 volts. It also says its "capacity" is 1200 mAhr. I can buy another battery that says it can deliver 2400 mWhr. Which one is better? Answer: the first one. Its capacity is 1200 mAhr. To convert that to mWhr, multiply by the voltage, to get 4800 mWhr. When doing comparison shopping, it is important to use the same units.

House electricity

The electricity that comes to your home is usually kept (by the power company) at a constant average voltage[7] of 110 volts. If you have no lights turned on, no refrigerator, no heaters, no TV, no anything, the voltage is still 110. The power company works very hard to keep the voltage at 110 even when you start using more appliances. The voltage doesn't change – only the current. The power you use is equal to P = volts x current, with volts = 110, so in the US, your power is

$$P(\text{in watts}) = 110 \times \text{current (in amps)}$$

The current that flows into your home depends only on how many appliances and other things you attach. A bright light bulb that uses 110 watts takes one amp. (P = 110 x 1 = 110 watts.) A heater that uses 550 watts takes 5 amps. (P = 110 x 5 = 550.) Amps just add, so if you have both the light bulb and the heater, then you will have 6 amps coming into your home.

In much of the world, things aren't so good. The voltage fluctuates, and you may get 50 volts for a while, and 150 at other times. That can cause havoc with some devices that work only for a limited range of voltages.

Resistance

Electrons moving through metal sometimes collide with the atoms of the metal, and they lose some of their energy to these atoms. This causes the metal to heat. The resistance depends on the type of metal (it is low for copper and high for tungsten), on the thickness of the wire and on its length. Resistance is measured in "ohms".

Resistance is what makes the tungsten filament in a light bulb get hot enough to glow. Resistance is what makes an electrical heater give off heat. Resistance is what makes your laptop computer hot. Resistance is what makes extension cords heat, and overheat if they carry too much metal.

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[7] By the "average voltage" I mean the RMS value. If you are interested, RMS stands for "root mean square" value. It is calculated by squaring the voltage, averaging it (since house current oscillates 60 times per second) and then taking the square root of this average value. In statistics, it is called the "variance."

The equation for resistance is simple: when you have an electric current I (measured in amps) flowing through a wire with resistance R, then the power P that is lost to heat (or converted into heat, if that's what you want) is:

$$P = I^2 R$$

For this equation, the lost power will come out in watts if I is in amperes and R is in ohms.

The wires used in the walls of your home heats up whenever you use electric current. For most homes, the wires are "rated" to be able to carry 15 amperes before the heating becomes enough to start a fire. To prevent this from ever happening, something is put at the beginning of the wire. In olden days, it was a fuse. A fuse is a material that has higher resistance than a wire, and is made of a material that melts at relatively low temperature. The wire inside the fuse was designed to melt when the current was more than 15 amps. Afterwards the fuse had to be replaced. Most modern homes now use "circuit breakers" instead of fuses. A circuit breaker is a switch that stops all current flow whenever the current exceeds the limit. But unlike a fuse, once the number of appliances plugged in is reduced, so that the total amount of current is reduced, the circuit breaker can be reset (i.e. the switch can be closed) rather than having to be replaced.

Superconductivity

Some metals have a strange property when they are cooled close to absolute zero: their resistance to current becomes zero. That means exactly what it sounds like: current flows with no loss of energy to heat. The bad news is that the temperature at which this happens is very low. For most of the 20th century, superconductors required that the temperature be within a few degrees Celsius of absolute zero.

Experiments have been done to see if the resistance is really zero. An electric current was started in a closed loop of wire, and the wire was kept cool. The presence of the current can be detected from the magnetism outside of the wire (we'll discuss this later in the chapter). Experiments to do this ran for many years, until the scientists involved became bored. No reduction in the current was detected; no loss to resistance was measured. The current just kept flowing.

The easiest way to cool a wire is to put it in a cold liquid. The original superconductors were kept cold by immersing them in liquid helium. (The liquid is made in special refrigerators, and then transported to the customer in dewars – glass containers that are similar to "Thermos" bottles.) Liquid helium boils at a temperature of 4 K, so as long as there is liquid, the temperature is low. The world doesn't have an infinite supply of helium. The helium we have comes from oil and natural gas wells (as described in Chapter 4 on Radioactivity). Most of the helium was once released into the atmosphere at these wells, because the need for it wasn't great enough to justify the expense of trapping it. But if superconductors someday become important, then helium will be even more valuable in the future. United States law now requires the oil and gas companies to recover and store the helium.

In 1972, the Nobel Prize in physics was awarded to Georg Bednorz and Karl Muller for their discovery of certain compounds that become superconducting at relatively high temperatures. Right now, the highest temperature superconductor works at a temperature of about 150K, equal to –123 C, equal to –189 F. That's pretty low for "high temperature" but it is the best anyone has done.

Part of the reason that scientists use the word "high" for this temperature, is that it is higher than the temperature of liquid nitrogen, which is 77 K. Recall that nitrogen is about 80% of air; it is extremely abundant, especially when compared to helium. Nitrogen can be liquefied for about a dollar a quart, making its cost comparable to that of milk (and some bottled water). Superconductors that can be kept sufficiently cold with liquid nitrogen are, in principle, much more practical.

So why aren't we using superconducting wires for all of our power transmission? The answer is that the high temperature superconductors are all pretty brittle, and it has been difficult to manufacture useful wires from them. Nevertheless, it is being done for some special applications. An experiment to see if such wires can be used for commercial electric power transmission is currently underway by Detroit-Edison power company.

Of course, if liquid nitrogen is used for cooling, then some power is lost – the power needed to produce replacement liquid nitrogen when it boils off.

There is a limit to the amount of current that superconducting wires can carry. That's because high current creates very strong magnetic fields (to be discussed shortly), and strong magnetic fields can destroy superconductivity just as much as can high temperatures. The current they carry depends on the cross-sectional area; some materials have been reported that can carry several million amperes per square centimeter of area.

Here is an amusing fact: according to theory, highly compressed hydrogen should become a metal. It is even possible that the core of the planet Jupiter consists of superconducting hydrogen.

Room temperature superconductors

Someday we may find a chemical that is superconducting at "room temperatures." Many people have searched for such materials, and every few years the newspapers report progress suggesting that such materials have been found – or are close to being found. Over the past thirty years, such reports have always turned out to be false, but there is no theoretical reason why superconductors could not exist. If and when they are found, they could transform the way we transmit power.

High tension power lines

Most long-distance transmission of electricity is done at extremely high voltage, several tens of thousands of volts. At these high voltages, you can sometimes hear the crackle of small sparks coming from these wires. Sometimes people refer to these lines as "high tension" lines. That's not because people who live near them get tense, but because "tension" is an old and outdated synonym for voltage.

There is an important reason that we use high voltage for such lines: they lose much less power to resistance than do low voltage lines. That's because, for a given amount of power transmitted, high-voltage lines have low current, and it is the current that causes resistive heating.

Since high voltage can make electricity dangerous, there are special devices that raise the voltage V and lower the current I, while keeping the power P unchanged (i.e. V times I remains unchanged). Such a transformer is called, aptly, a "transformer." We'll talk about how they do their work after we have discussed magnetism. Some transformers are near homes, so they don't lower the voltage until they are as close as possible. Many of these transformers are filled with an insulator known as PCBs.[8] When it was discovered that PCBs can cause cancer, it began an ongoing campaign to eliminate these liquids and replace them with something that was less carcinogenic.

The Laws of Electricity and Magnetism

The electric force between two electrons is given by a law that looks very much like the gravitational law. But instead of putting in the mass of the electron, the equation requires something we call the electric charge q. Suppose we have two particles, one with charge q and the other with charge Q. (The big Q might be a nucleus, containing lots of protons.) Then the electric force between them is given by

$$F = K\, q\, Q / r^2$$

Notice how much that looks like the gravity equation! Where the gravity equation has m, we now have q. Where it had M we have Q. And where it had G, we now have K. The electric charge for one electron is $q = -1.6 \times 10^{-19}$ coulombs. For a proton, $Q = +1.6 \times 10^{-19}$ coulombs. The fact that this is exactly equal (but opposite in sign) to that of the electron is one of the great unexplained mysteries of physics. The constant K is a number designed to make the values come out right. With the charges in coulombs (as I gave), and the distance in meters, then $K = 9 \times 10^9$. No, you don't have to know this. It is useful

[8] PCB stands for "polychlorinated biphenyl." Polychlorinated means the molecule contains multiple molecules of chlorine. Biphenyl means that the organic molecule has two "phenyl" groups attached, each consisting of an oxygen and hydrogen atom. Physicists usually don't know this, and neither do you.

only if you have to do calculations. (Most professional physicists have this number memorized.) When F comes out negative, the force is attractive. When it is positive, the force is repulsive.

The fact that you divide by r^2 means that as you separate two electrons, the force becomes much weaker, just as in gravity. By the way, you may hear that both gravity and electricity are "inverse square laws." All that means is that both equations have a division by r^2.

Current flow is circular – and bird safety

A seemingly peculiar property of current flow is that it is almost always circular. Wall plugs have two metal parts – one for the electrons to flow out of, and the other for them to return into. Light bulbs have two attachments: a small metal connector right at the bottom of the bulb, and the metal screw. Electrons flows into one, through the filament of the wire (where they lose energy and heat the wire) and out the other.

But why must there always be two connectors? The reason is that electrons repel each other. If electrons flowed in, but not out, then they would accumulate in the bulb, and they would repel other electrons.

Think about how electrons move in wires. They come from metal atoms, but jump from one atom to the next. When they do this, they leave behind the atom, which then has a net positive charge. (The protons used to balance the electrons, but with one electron missing, the atom has an excess of positive protons.) Doesn't that positive charge pull the electron back? Yes – unless there is another electron that moves in.

Electric current will flow only as long as the moving electrons are replaced. When electric current flows, the moved electrons must always be replaced. If they aren't, then the accumulating electrons repel others, and the current flow stops.

When a bird lands on a high voltage line, some electrons will immediately flow into the bird. There will be a little bit of current. But with nowhere to go, the electrons soon repel other electrons from coming, and the bird is safe. Very few electrons are needed to stop the flow. But if a big bird were to land on two lines, each one with opposite voltage, the results would be very different.

The quantization of charge

One of the most mysterious laws of physics is that charge is quantized. This means that for every particle measured, the charge found on it is an exact multiple of the charge found on the electron. The proton charge, for example, is (as nearly as we can tell) exactly equal in magnitude to the electron charge. It has the opposite sign of charge, and that's why electrons and protons attract each other. But all other measured particles also seem to have a charge equal to some multiple of the electron charge.

Nobody knows why charge is quantized, although many theories have been proposed. One of the most elegant is due to Paul Dirac, who won the Nobel Prize in 1933 for his work combining the Theory of Relativity with Quantum Mechanics.[9]

We now think that charge is quantized, but the basic unit may not be the electron charge, but instead is 1/3 of the electron charge! Particles with 1/3 and 2/3 electron charges are believed to exist within the proton. They are called quarks. Despite this, it appears that such "fractional" charges can only exist in very close distances, and that there must always be nearby fractional charges that make the total charge of any particle be a multiple of the electron charge. In other words, deep inside a proton the charges can be fractional (always in multiples of 1/3) but such particles can never exist separated from others. This mysterious fact is called "confinement" and we don't really know why it is true. (Of course, theories for confinement have been proposed, but we don't know which, if any of these, are right.)

Magnetism

A mysterious feature of electricity is that there is a second kind of electric force – that we call magnetism. In the last section we saw that the ordinary electric force comes from two electric charges q and Q separated by a distance r. But there is another force that occurs only if the charges are moving! Thus, this is a force that occurs between electric *currents* rather than between static charges. The equation for magnetic force is given by an equation that looks very much like the equation for electric force.

Optional: the magnetic force equation

> The magnetic force equation is called the "Biot-Savart Law." We show it here just because it is so similar to the electric force equation, even though we will not use it for any calculations. The magnetic force F is given by:
>
> $$F = K_M S \frac{C_1 C_2}{r^2}$$
>
> In this equation C stands for a "current segment" – it is the current (measured in amperes) multiplied by the length (in meters) of wire in which that current flows. There are two such segments exerting forces on each other. K_M is a constant (to make the units come out right), and S is a geometric term (with value between +1 and –1) that depends on the relative positions and angle between the two wire segments.

[9] Dirac showed that if one magnetic monopole existed somewhere in the universe (and we'll discuss magnetic monopoles shortly), then the quantization of charge would be a consequence of the quantization of angular momentum. And that is explained by the theory of quantum mechanics – it is a result of the rotational symmetry of the Universe. (This is not required material for this course.)

> Notice that this equation looks very much like the force equation between two charges. It depends on the strength of the currents C1 and C2 (instead of the strength of the charges) and it depends on $1/r^2$, just like the charge equation. This formula is known as the Biot-Savart equation.

To calculate the force between long wires, you have to add together all the forces between each pair of wire segments. For long wires, there are a huge number of such pairs, and that makes the problems complicated. For simple cases (e.g. two long strait wires) the total force can be worked out mathematically; the result is that two parallel wires carrying current in the same direction will attract each other. For more complicated cases, such as wires wrapped in large loops, the calculation is usually done on a computer.

Permanent magnets

The most common form of magnetism comes from the tiny electric currents that exist inside the atom. All materials have such currents flowing, but for some very special materials the currents in different atoms all flow in the same direction. Materials that have such oriented currents constantly flowing are called “permanent magnets,” In permanent magnets, the electric flow in the atoms is typically in little circles, and if all the circles are in the same direction, then the result is a piece of material than can have a big magnetic force on other currents, or on other permanent magnets.

A surprising aspect of this circular flow is that it can come from individual electrons that are spinning, i.e. they rotate while staying in place. So the electron need not move. The spin of an electron creates a magnetic field in the same way that you would get from an electron moving in a circular path. In a permanent magnet, a large number of electrons in the material all spin in the same way.

loadstones and compasses

The first known magnets were natural rocks containing iron ore, known as “loadstones.” A magical feature of these stones was that if you suspend them (by a string, or by floating them on a piece of wood), that they would tend to rotate until one end was pointing north. This became an enormously important discovery, since it could be used to tell direction. It was called a “compass” and was so valuable that it was originally a deeply held secret. Even on a completely cloudy day, far out at sea, you could tell which direction was north. The word loadstone derives from the Old English word “lode” which means way or path; a lodestone helps you find your way. The impact that the magnetic compass had on history is difficult to know. In 1620, Francis Bacon ranked it with gunpowder and the printing press as the three inventions that had revolutionized the world.

For hundreds of years, nobody understood why one end of the loadstone pointed north. Some people assumed that the loadstone felt some attraction towards the North Star. The secret turned out to be that the Earth itself is a large magnet, and the north pole of the loadstone was being rotated by the magnetism of the Earth.[10] The “north pointing pole” of the loadstone was often referred to as simply “the north pole” of the magnet. The other end was called, naturally, the “south pole” of the magnet.

Another major discovery was that new magnets could be made by rubbing iron needles (in one direction only, not back and forth) repeatedly against a loadstone. The needles were called magnets, and you could make as many as you wanted. These then could be used for compasses.

Now we can make permanent magnets that have much more powerful magnetism than do the original loadstones.

kissing stones

A second magical feature of loadstones is the fact that if you put two of them near each other (north pole near south pole), there is a force of attraction between them; they are drawn to each other and they touch. Because of this property, the Arabs called them *tzhu shih*, which means "loving stone.” The French word is similar: *aimant*, literally stones that like each other.

But magnets also repel each other. If you place two north poles near each other, they repel. Likewise for two south poles. But north and south poles attract each other.

magnetic monopoles

As far as we can tell, magnetism always comes from electric currents. But north poles of magnets repel each other, just as positive electric charges repel each other. South poles repel each other, just like negative charges repel each other. And opposites attract. This has led many people to speculate that there must be magnetic charges, similar to electric charges. These hypothetical objects are called “magnetic monopoles.” Permanent magnets behave as if they have a concentration of such charges at their ends. Yet we know this is not really true. All present permanent magnets actually work because of currents flowing within their atoms.

If you take a magnetic needle, one end will be the north pole, and the other end will be the south pole. You might think that you can break off the north pole by cutting the needle, but if you do that, a south pole forms at the broken end. Magnets appear to always have both north and south poles, no matter how they are made. That’s because a broken magnet still consists of rotating electric currents, and those always produce north and south poles.

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[10] There are records of magnets being used in China in the first century. The first records in Europe date from a manuscript written in 1187 by Alexander Neckam. In 1600, William Gilbert (the physician to Queen Elizabeth I) figured out that the Earth was a giant magnet. He wrote, in Latin, “Magnus magnes ipse est globus terrestris.” That can be poetically translated as, “A magnificent magnet is the terrestrial globe.”

Diagram:
a loop of current, with a north pole emerging from one side
and a south pole from the other.

That doesn't mean that magnetic monopoles don't exist somewhere, or that they can't be manufactured. Many projects have been made to search for them, or to try to make them. Some theories (e.g. superstring theories) predict that they should exist, or at least, it should be possible to make them. Searches have been made in materials that have been exposed to extremely energetic collisions, since those may have created monopoles. Materials studied have included lunar rock (exposed to energetic cosmic rays for billions of years) and metals placed at the end of large particle accelerators ("atom smashers").

If magnetic monopoles could be made, they would be valuable. They could be accelerated to very high energy by ordinary magnets, and this could be a convenient way to create such radiation (which would have applications in medicine and elsewhere).

the short range of magnetism

Because magnets (until monopoles are discovered) have both north and south poles, once you get a reasonable distance away from one, the two fields tend to cancel. This cancellation tends to make the net magnetic field fall off faster, not with an inverse square law ($1/r^2$) but with an inverse cube law ($1/r^3$). That means that if you go twice as far away, the force is reduced by a factor of $2^3 = 8$. So when twice as far away, the force is 2x2x2 = 8 times less. If you are three times as far away, the force is 3x3x3 = 27 times weaker.

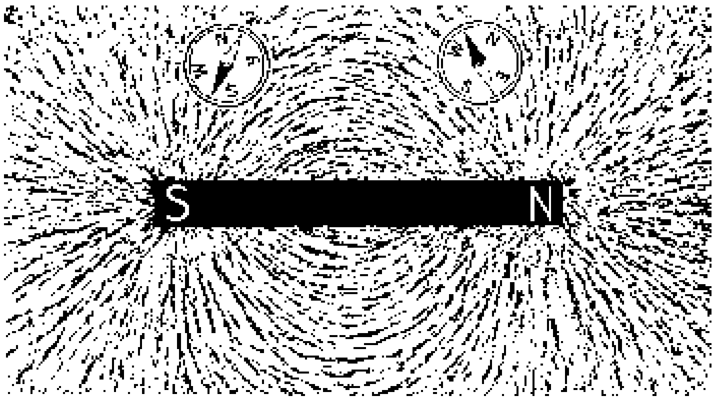
The result is that magnets are very useful for short distances, but don't work very well for larger distances.

Electric and magnetic fields

It was once thought that one electric charge put a force directly on other electric charges. Now we know that there is something intermediate that happens. The electric charge creates something that we call an electric field, that fills up space. It is this field that puts the force on the second charge. The way we know that this is true is that we can quickly remove the first charge, and yet the field remains there, if only for a very short time. We also know that the field can be made to vibrate, a phenomenon that gives rise to something known as an electromagnetic wave. It turns out that light, radio signals, and x-rays are all examples of electromagnetic waves.

The key idea here is that charge produces an electric field, and this electric field can produce a force on other charges. Likewise, moving charges (currents) produce a magnetic field, and this field can exert a force on other moving charges (currents).

Magnetic fields can be visualized by sprinkling iron filings near a powerful permanent magnet. It is possible, but harder, to "see" strong electromagnetic fields since they tend to produce sparks. An illustration of this is shown below. Two compasses have been placed near the magnets that illustrate the direction that they would point.



(borrowed from http://www.lhup.edu/~dsimanek/scenario/analogy.htm)

Electromagnets

If you put a wire into the right geometry, you can arrange it to exert a very strong electrical force on other currents, or on a permanent magnet. A common geometry to do this is called a "solenoid." It is just wires wrapped around a cylinder. Turn on the electricity, and you have a strong magnet. Turn it off, and the magnet is turned off. Reverse the current, and the magnetism is reversed (i.e. the north pole becomes a south pole).

Auto door locks

Electromagnets have lots of uses. In automobiles, they are used to lock and unlock doors. (Click the door switch and a solenoid electromagnet pulls a permanent magnet.)

Speakers and earphones

Small electromagnets are used in speakers and earphones to create sound. Typically such devices have a small permanent magnet, and an electromagnet. Electric current goes through the electromagnet, and that causes an attraction between it and the permanent magnet. Then the current is reversed, the magnetism of the electromagnet is reversed, and now the two magnets repel. Usually the electromagnet is made very light-weight, and it can move back and forth in response to these reversing forces. The electromagnet vibrates in a way that follows the oscillations of the current. In an earphone or speaker, a piece of paper attached to the electromagnet oscillates along with it, and that pushes against the air, making the air vibrate. Air vibrations reach the human ear, and we hear them as music. (We'll discuss this further in the chapter on waves.)

Junked autos

Huge electromagnets are used to lift junked automobiles. But how? Automobiles are not normally magnets, so why should they be attracted? The answer is that they usually contain large amounts of iron, in the body or in the engine. When a magnetic field (from an electromagnet) is applied to iron, the iron becomes magnetized – i.e. it behaves in the same way as a permanent magnet, but only as long as the field is applied.

Most materials behave this way only a little. The magnets they become are very weak. But some materials become very strong magnets when an external field is applied.

Magnetic materials – the special role of iron

I said earlier that permanent magnets are made from materials in which a large number of the electrons are spinning in the same direction. Ordinary iron is not normally a permanent magnet because its electrons, even though they are spinning, are all spinning in different directions.

But if you apply an external magnetic field, e.g. by an electromagnet, then that puts a force on these spinning electrons. For iron atoms, it tends to make the electrons all spin in the same direction, and that makes the iron into a magnet – as long as there is current flowing in the external electromagnet. We say that magnetism is *induced* in the iron.

That's why a permanent magnet can pick up a paperclip. When you bring the permanent magnet near the paperclip, magnetism is induced in it, and then the permanent magnet and the paperclip attract each other.

Here is how an electromagnet can lift a piece of iron, as in a junked car. The electromagnet is turned on, and it makes a strong magnetic field. This magnetism aligns the electron spins in the iron of the car, turning it into a magnet. It is an induced magnet. For iron, the two magnets (the electromagnet and the induced iron magnet) attract each other.

Induced magnetism can also be used to make magnetic fields that are much stronger. If you place iron inside the cylinder of an electromagnet, then the weak magnetism of the current is strongly enhanced by the induced magnetism of the electron spins. And it doesn't stop there. The induced magnetism of some of the atoms induces even more electrons to spin in the same way. The strength of the magnetism grows dramatically, until the magnetism is hundreds of times stronger than it would have been without the iron. This kind of magnetic amplification is so useful that most electromagnets uses iron cores.

remnant magnetism and Curie temperature

When the electric current is turned off, so there is no external applied magnetic field, then most of the induced magnetism goes away. But usually some of the electrons remain lines up with each other, so there is a small *remnant* (that means remaining) magnetism. That remnant magnetism is one way to make permanent magnets. The remnant magnetism goes away (i.e. the electron spins get mixed up) if you heat the iron enough. In fact, there is a temperature called the "Curie temperature" at which all the remnant magnetism goes away. The Curie temperature was named after Pierre Curie, who was the husband of the more famous Madam Marie Curie.

Remnant magnetism can be very useful (to make permanent magnets) or it can be a real nuisance. If you bring an iron screwdriver close to a strong magnet, it becomes magnetized; when you take it away, there may be some remnant magnetism left. If that is true, the screwdriver may attract screws or little bits of iron, and that can be useful or annoying. Old watches (in pre-electronic days) would become magnetized if brought close to a magnet, and then the pieces within the watch would attract each other, and that was usually enough for the watch to stop working. Watch repair experts would fix the watch by putting it back in a changing magnetic field that would slowly reduce the magnetization to zero.

Samarium cobalt

In the last few decades, a particularly strong type of permanent magnet was invented. The first was made out of a compound called samarium cobalt. Samarium is an element known as a "rare earth." Now other similar compounds have been found, and these magnets are often called "rare earth cobalt magnets."

These magnets are so strong that they can be dangerous. If you break one (maybe by dropping it) and it breaks in such a way that the two pieces repel each other, then pieces can go flying apart at such high velocities that they can hurt someone. When used in earphones, they are packaged in such a way as to prevent the magnet from being struck with a shattering blow.

Samarium cobalt magnets have become widely used in recent years to make small earphones, small motors (I'll discuss these in a moment), and other small devices that produce motion from electrical signals.

Magnetic recording

Induced magnetism is also the basis behind magnetic recording, and that includes videotape, computer hard drives, and MP3 players. In these devices, a very small electromagnet induces a magnetism in a small region of a magnetic material. In the adjacent region, it can induce similar magnetism, or a reversed magnetism. The signal is stored in the magnetic material by these small regions. For example, if adjacent regions have the upward direction induced in a series of north and south magnetic poles: N, N, S, S, N, then this could be a way of recording the digital signals 1, 1, 0, 0, 1. This is the basic principle for all magnetic recording.

Some magnetic recording devices record this pattern on flexible tape (e.g. cassette players, videotape recorders). The tape has a very thin layer of magnetic material deposited on its surface. To get a lot of information on the tape, the magnetic regions must be very small. A computer hard drive has magnetic material distributed on the surface of a rotating disk. As the disk moves under the electromagnet, different places have different induced magnetism. These days, these regions are typically a micron or smaller in size.

The magnetic recording can be "read" by another wire. When a moving magnet passes a wire, it makes a small amount of electric current flow, and that current can be detected. In modern "hard drives" the wire is a special material in which the resistance of the wire depends on the magnetic field. By measuring that resistance, the wire gives information about the magnetic field.

finding submarines

A submarine is made of steel, and when it sits in the Earth's field, it becomes a big magnet. During World War II, scientists realized that you might be able to find submarines deep under water by detecting this magnetism. Because magnetic fields get weak at large distances (as $1/r^3$), this method doesn't work for very deep submarines, but it is still used when submarines are within a few hundred meters of the surface.

Electric motors

Electric motors are really based on magnetism. In an electric motor, the wires are wound in such a way as to create a strong magnetic field. In the simplest version of a motor, this magnetism is used to pull or push on a permanent magnet. If the current is reversed, then the permanent magnet can be made to move in a circle. That is how an "electric" motor works.

It is not necessary to use a permanent magnet. Many electric motors use two electromagnets, one which is stationary and one which rotates. The electric current is switched in such a way that the force of one magnet on the other pushes the rotating magnet in circles.

As long as thick wires are used, the electric resistance can be small, and electric motors can be very efficient, i.e. they can turn the electric power into mechanical motion with very little loss to heat. Hybrid automobiles use the electricity stored in batteries to drive the wheels using electric motors.

Electric generators

The most effective way to make electricity for commercial use is by moving a wire through a magnetic field. When this is done, it is called an electric generator. Essentially all the electricity that you use is made this way. You also use some electricity from batteries (in flashlights and in your auto), but that is only a very little bit compared to the rest.

A wire made of metal has electrons in it that can move. When you move this wire through a magnetic field, then the electrons move with the wire. Moving electrons, just as with any current, feel a force from the magnetism. If you move the wire perpendicular to the direction of the wire, then the force of the magnetism will be along the wire, so the electrons will be pushed along the wire – that is, current will flow along the wire.

At nuclear power plants, the nuclear chain reaction is used to produce heat, and that turns water into steam. The steam drives propellers (technically called a "turbine"), and those are used to drive wires through a magnetic field, producing electricity.

In a coal burning power plant, the coal is burned to produce heat – and from there on, the power plant works the same way, ultimately producing electricity by pushing wires through a magnetic field.

In a gasoline burning power plant, or one that uses natural gas, the fuel is burned to produce heat, and from there on the process is the same.

In a hydroelectric plant, water coming from the reservoir is used to turn wheels, and these push wires through magnetic fields, etc. etc.

Once your automobile has started, it no longer needs a battery. From then on, all the electricity it needs (for spark plugs, and to light the headlights) is made from the gasoline engine, which turns an axle (called a crankshaft) which turns a wheel that moves wires through a magnetic field.

Dynamos

To work well, a generator needs a strong magnetic field. For small generators, that can be made out of permanent magnets. But for big generators, the magnets must be electromagnets. Guess where they get the electricity to run the electromagnets.

That's right. They get the electricity from the generator! When this is done, the generator is called a dynamo.

This sounds paradoxical, but it really works. Most large generators are dynamos. It sounds like you are getting something for nothing, but that isn't true. It takes energy to push the wire through the magnetic field,[11] and all the electric energy that emerges (in the current in the wire, and in the magnetic field) comes from the energy that you put in.

The North Pole is a South Pole

As we discussed earlier, the Earth is a great magnet. That's why compasses point towards the poles. But the Earth's magnetism is not perfectly aligned with the axis of the

[11] The current that flows in the wire interacts with the magnetism, and produces a force that resists the motion. That's why you have to do work to move the wire.

Earth's spin, so the direction that the compass points is not true north but a different location. The magnetic pole is located at a latitude of about 75 degrees, in northern Canada near Baffin Island. Maps often have a little symbol on them that shows the difference between magnetic north and true north.

The situation is much worse on some of the other planets. On Uranus and Neptune, the magnetic poles are 60 degrees away from the poles of the rotation axis.

You should be aware of a semantic problem in our terminology. The north pole of a compass needle points towards the Earth's magnetic pole. But the north pole of a magnet is attracted to a "south pole" of another magnet. Thus, magnetically speaking, the magnetic pole that is up in Canada is really a south magnetic pole!

Einstein's mystery

When Gilbert deduced that the Earth was a magnet, he naturally assumed that it was a permanent magnet, perhaps from large deposits of loadstones. But we now know that rocks below the Earth are hot, from the Earth's radioactivity. At a depth of about 30 km, the temperature is higher than the Curie temperature, so all magnetism must disappear. These paradoxes led Albert Einstein to list the origin of the Earth's magnetism to be one of the greatest unsolved problems of physics.

We now believe we know the answer: the Earth is a dynamo. We don't know in detail how this works, but we understand the general picture. The early Earth (4.5 billion years ago) was very hot, and most of the iron melted and sank to the center. It is still there; if you go about half-way to the center of the Earth, the material changes from rock to molten iron. Moreover, this iron is in constant flow, from heat that is being released from a small solid iron core deep within. This flowing iron behaves like a dynamo. When liquid iron moves in a magnetic field, electric currents flow (just as in a moving wire). The arrangement of flow in the core is such that these electric currents circle around to create the magnetic field, just as they do in a commercial dynamo generator.

This picture is verified by computer and mathematical models, but it is hard to be sure, since the center of the Earth is far harder to reach than the surface of the Moon.

The Earth Flips – its magnet

As ocean animals die, and drift to the bottom of the sea, they eventually form new layers of rock. These rocks become slightly magnetized by the Earth's magnetic field, and then they hold that magnetism for millions of years. If we study the layers of rock, and measure their ages (from potassium-argon dating, as discussed in Chapter 4), we can read the history of the Earth's magnetism.

From these records we have learned that the strength of the magnetic field changes slowly with time. But much more startling is the discovery that from time to time the magnetism of the Earth flips! That means that if you took a present-day magnetic compass back into the past, that the north-pointing needle would point south instead of north.

The last flip was almost a million years ago, and such flips (at least in recent times) seem to occur, on average, once or twice every million years. The flip takes several thousand years to happen, but in the geologic record that seems very fast.

We don't know why the magnetism flips, but several theories have been proposed. It turns out that the actual flow of liquid iron that drives the dynamo doesn't have to change. Instead only the electric current has to reverse. When that happens, the magnetism will flip too. There are some theories that attribute the change to the chaotic behavior seen in some dynamo models.

My favorite theory (also unproven) is that the flip magnetism consists of two steps: a destruction of the dynamo flow (perhaps triggered by avalanches of rock at the liquid/rock boundary), followed by a rebuilding of the dynamo in the opposite direction.[12]

Now here is a riddle: make sense of the following words. "The Earth's North Pole is a south pole. However, about a million years ago, it was a north pole."

Flipping magnetism and geology

The fact that the Earth's magnetism flips every million years or so has been enormously useful in geology and related fields such as climate study. It is valuable because we often cannot measure the age of a rock from its radioactivity. For example, rocks often don't contain enough potassium for the potassium-argon method to be used. However, most rocks formed under the sea preserve a record of the Earth's magnetism. We can see a pattern in the layers, almost like a fingerprint, with some flips coming close to each other in time, and others with wide spacing. Once this pattern is known, then we can correlate the patterns at different locations around the Earth. We don't know how old a layer is, but at least we know it is the same age as another rock somewhere else on Earth.

But we can do even better. If we search long enough, we'll probably find a rock that was formed near a volcano. Volcanic ash contains lots of potassium. If we can use potassium-argon dating to obtain the age of this one rock, then we immediately know the age of rocks all around the world that are at the same position in the geomagnetic pattern.

This is important, in turn, because these other rocks often contain unique records of their own. Some of them record the patterns of previous climate. If you put all this together, you can figure out when the last ice age occurred on Earth, how long it lasted, and how

[12] This theory is my favorite, in part, because it is my theory. It was published in the journal Geophysics Research Letters, and is available online at http://muller.lbl.gov/papers/Avalanches at the CMB.pdf.

quickly it ended. In this way, much of our knowledge of the past has used the Earth's magnetic field flips.

Earth's magnetism and cosmic radiation

Just as electrons flowing in a wire feel a force from a magnetic field, cosmic rays coming from space feel a force and are deflected by the Earth's magnetic field. This prevents a large number of these particles from hitting the top of the Earth's atmosphere. Some people have speculated that when the Earth's field collapses (as during a magnetic reversal) that life on Earth is exposed to this deadly radiation. This idea has been widely spread by science fiction movies such as "The Core."

If the field collapses, then it is true that the cosmic rays will hit the Earth's upper atmosphere. But the atmosphere is the true shield, and even without the field, the radiation that reaches the Earth's surface will increase by only a few percent.[13] Thus, the field collapse will not significantly affect life.

Transformers

An electric generator works by moving a wire past a magnetic field. It would work equally well if the magnet were moved past the wire.[14] In fact, the magnets don't actually have to move; it works equally well if their magnetic field is just changing, and that can be done by changing the current in an electromagnet.

If all the ideas in the previous paragraph are put together, we get one of the great inventions of all time: the electric transformer. In a transformer, there is a coil of wire called the primary. Changing electric currents in this primary create a changing magnetic field. The changing magnetic field passes through a second coil of wire called the secondary, and it causes current to flow in the secondary.

One remarkable fact about a transformer is that it can pass energy from the primary coil to the secondary coil very efficiently, with almost none being lost. The primary and the secondary don't touch each other. The energy is all passed through in the form of magnetism!

What makes the transformer so valuable is the fact that the number of loops of wire in the primary and secondary can be different, and the result is that the voltage and current in

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[13] At the geomagnetic pole, the Earth's field presently gives no shielding whatsoever. This results in a much stronger cosmic radiation at the top of the atmosphere, and yet the radiation at the bottom of the atmosphere is only slightly greater than elsewhere on Earth.

[14] This is true, but it isn't really obvious. The discovery that it was true was led to Einstein's postulate that the laws of physics are identical regardless of the way you are moving, and that took him to the Theory of Relativity.

the two coils will be different. A transformer transforms high voltage electricity to low voltage electricity, or the other way around. It is transformers that take the high voltage from power lines and reduce the voltage to make it safe for our homes. And they all work using magnetism.

If there is any iron near the transformer, then that iron may vibrate as the magnetic field changes. You can often hear a "hum" from a transformer that is doing this. Of course, that hum means that some energy is being lost from electricity to sound, so high quality transformers are built so this doesn't happen.

The Tesla Coil

Nikolai Tesla, a scientist who worked with Thomas Edison, invented a very high voltage transformer we now call a "Tesla coil." One of his tricks was to make the current change very rapidly, and that generated very high voltages in the secondary. A tesla coil can be used for a dramatic demonstration in the classroom, with continuous sparks over a foot long. At the same time, the sparks are not particularly dangerous. When the transformer raises the voltage of electricity, it must also lower the current – since the power is current times voltage, and the power doesn't change. So a Tesla coil can create extremely high voltage sparks, but they release relatively low power.

The demonstrations used in the Berkeley Physics Department can be seen at these web pages:
http://www.mip.berkeley.edu/physics/D+75+04.html
http://www.mip.berkeley.edu/physics/D+75+08.html

AC vs. DC

Most of our homes use alternating current electricity, abbreviated "AC." In AC, the current is constantly changing, cycling its flow from positive to negative and then back again, 60 times every second. That's what we mean when we say that house current is 60 cycles – that is short for 60 "cycles per second." There are 60 minutes in an hour, 60 seconds in a minute, and 60 cycles in a second.

A new terminology is to use the name "Hertz" to mean "cycles per second." Hertz is abbreviated Hz. In the U.S. we use 60 Hz electricity. In Europe, they use 50 Hz.

Batteries give DC ("direct current"). So why do we use AC in our homes? The answer is because AC works naturally with transformers. High voltage (and low current) is used in high tension power lines to bring electricity to our homes. But before it enters the home, a transformer changes it to relatively low voltage (110 volts) and relative high current (up to about 15 amps).

It was not always obvious that our electrical system would be based on AC. In the late 1800s, Thomas Edison believed the future would be DC. His rival, Nikola Tesla, was a believer in AC. Tesla argued that AC would allow the use of high voltage, and that meant that the power generators could be far from homes. Edison thought that unnecessary. He believed there could be electric power generators just a few blocks from every home, so low voltage (high current) could be used. The rivalry got unpleasant. At one point, Edison tried to convince the public that high voltage was dangerous by convincing the State of New York to use high voltage to execute condemned prisoners. He even arranged to make a movie (another Edison invention) of the electrical execution of a condemned elephant named Topsy.[15]

In the end, Tesla won. We use AC, not DC, and our power plants are located far away, not on every street corner. Our wall-plugs deliver 110 volts at 60 Hz. Many of our homes have a separate set of wires for 220 volts, used on devices that take much more power, such as air conditioners. The higher voltage allows less current to be used (for the same power), and that reduces losses from resistance. In Europe, virtually all appliances uses 220 volts (at 50 Hz). This higher voltage is more dangerous, but it does reduce resistive loss that turns power into heat.

Magnetic levitation

Ordinary iron, when exposed to a magnet, becomes a magnet itself, and is attracted to the original magnet. But some materials behave differently. When exposed to magnetism, they become magnets themselves, but in the opposite sense. The part which is exposed to the north pole of the magnet becomes a north pole itself, and instead of being attracted, it is repelled.

Such materials are not common, and that is why our experience is that magnets "attract" things. Liquid oxygen is one of the uncommon materials that is repelled by ordinary magnets. But superconductors are also repelled. When exposed to magnets, currents start flowing inside superconductors in just such a way as to create a repulsive force. If you place a small superconductor on top of a magnet, the force can make the superconductor "levitate" above the magnet, with the repulsive force countering gravity.

If you have a changing magnetic field, created by an electromagnet with alternating current, then levitation can be done with ordinary metals. The changing magnetism will cause currents to flow in the metal, and these currents will create magnetism that repels the original magnet. This approach can be used to levitate large objects. For a demonstration of this effect, see http://www.mip.berkeley.edu/physics/D+15+24.html.

Levitation can also be done with moving magnets. If a strong magnet (samarium cobalt, or a strong electromagnet) is moved over a conductor, then electrical currents will be induced in the conductor. Those create a magnetic field which repel the original magnet. This approach is used commercially in magnetically-levitated trains in Japan. At slow

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[15] Topsy was a "bad" elephant, and had killed a man. She was to be "put to sleep" when Edison argued that electrocution would be more humane. Topsy's story likely inspired Walt Disney's movie "Dumbo."

velocities, there is no levitation (since the induced magnetism requires a rapidly changing – or moving – electrons). As the trains moves faster, the magnet moving over the rails induces stronger and stronger currents, until finally the magnetic repulsion lifts the wheels off the tracks. The advantage of magnetic levitation is that it avoids all the friction of contact. However, the currents flowing in the rails do lose some energy to electrical resistance, and that can be a serious limitation. Superconducting rails would avoid this problem, but they have to be kept cold. With all these problems, magnetic levitation has not proven to be as successful as some futurists have predicted. That could change if we ever develop room-temperature superconductors.

Rail guns

In Chapter 3 (on gravity) we discussed the limitations of launching objects into space using chemical fuels. The problem was the exhaust velocity of such fuels was only one or two km per second, so it was hard to use them to push objects that had to go 11 km per second. But using magnetism, we can overcome that limit. The device that does this is called a rail gun.

The simplest version of a rail gun consists of two long parallel metal rails, just like those used for railroads. A high voltage is placed across the ends of the rails, and a piece of metal (called a sabot) is placed across or in between the two rails. High current flows from the end of one rail, down the rail, across the metal, to the second rail, and back. The high current in the rails creates a strong magnetic field, and this puts a force on the current flowing through the metal sabot. As a result, the sabot is pushed down the rails. Theoretically, rail guns can launch a sabot at extremely high velocities.

Rail guns are under development by the Navy as a way of shooting down missiles attacking a ship, and they may one day be used to launch materials from the moon.

Optional: Automobile Battery

When you buy an automobile battery, it will have on its label the voltage, the "cold cranking" amperes, and the "reserve capacity." For a good (expensive) car battery, the numbers might look like this:

Voltage	12 volts
cold cranking amperes	800 amps (at 7.2 volts)
reserve capacity	120 minutes = 7,200 seconds (at 10.2 volts)

These numbers are defined in a particular way. The "cold cranking amps" represents the current that the battery will deliver for 30 seconds, without the voltage dropping below 7.2 volts. (When high current comes from the battery, the voltage of the battery drops, because of resistance within the battery itself.) Having lots of cold cranking amps is important when you are starting your car, because that is when you use the highest current. In the example above, the battery can deliver 800 amps for 30 seconds at a voltage of 7.2 volts. The power it delivers is P = V I = 12 x 800 = 9,600 watts. It delivers this for 30 seconds. The energy it delivers is E = P t = 9600 x 30 = 288,000 joules = 70,000 calories = 70 Calories.

The "reserve capacity" is defined as the time for which the battery can deliver 25 amperes of current without the voltage dropping below 10.5 volts. This is important, for example, if you leave your lights on by accident when you park your car. The power is P = V I = 10.5 x 25 = 262 watts. It can deliver this for 7200 seconds. The energy delivered is E = P t = 262 x 7200 = 2,000,000 joules = 500,000 calories = 500 Calories. Note that the battery is MUCH more efficient at the lower current: the energy it can deliver is 500 Calories instead of only 70 (when cold cranked).

An automobile battery weighs about 45 lb = 20,000 grams. So the energy this battery can deliver per gram is 500/20,000 = 0.025 Cal/gm. This is the value that we used previously when discussing the difficulties of making a useful electric car; recall that the energy stored per gram for gasoline is about 10 Cal/gm, i.e. 400 times larger than for the car battery.

Optional: more on Flashlight Batteries

When you buy a flashlight battery, it doesn't give you ANY specifications except the voltage, and vague claims about it being "long lasting" or "durable". For those of you who someday pass laws, please change that! Why can't flashlight batteries be labeled in the same manner as automobile batteries?

Looking on the web, I found that typical "D Cell" batteries have an energy rating of 1200 mAhr. That means they can deliver 1200 milliamp = 1.2 amps for one hour, i.e. for 3600 seconds. Since the voltage is 1.5 volts, the power delivered in that hour would be 1.2 x 1.5 = 1.8 watts. The energy is E = P t = 1.8 x 3600 = 6480 joules = 1.6 Calories. The battery weighs 135 grams, so the energy is 1.6/135 = 0.01 Cal/gm. This is a factor of 2.5 worse than we found for automobile batteries. So flashlight batteries, made to be safe, dry, and easily handled, have 2.5 times less energy per gram than car batteries.

Optional: more on the history of electric power

In the late 1800s, Thomas A. Edison had invented the light bulb. This had such a great impact on the world, that even today we uses images of a person thinking -- and the image of a light bulb suddenly appearing in his thoughts -- as a cartoon of a person having a great idea.

The man who most disliked Edison's invention was a man named John D. Rockefeller, who had made a fortune selling oil. At that time, oil was used almost exclusively for heating and lighting. Electricity (which could be made by burning coal -- which boiled water, which ran a turbine, which ran a generator), could make his oil virtually worthless. Fortunately for him, right about that time, improvements in oil-driven engine technology (in particular, the "internal combustion engine") made possible a new invention: the auto-carriage, also known as the auto-mobile. So Rockefeller's fortune was preserved.

Edison wanted to "electrify" New York City. His vision was to put metal wires on poles above the city streets, to carry current to every house. Because energy is lost in those wires (from their resistance), the energy could not be transported very far. But he saw that a creating no real problem: he would place an electric power generator in every neighborhood, so the wires would never be more than a few blocks long.

Edison had hired a very talented engineer named Nikola Tesla. But Tesla had quit in a huff. Tesla claimed that Edison had patented all of Tesla's ideas in the name Edison, and had not given Tesla the monetary rewards that he had promised.

Tesla had become enamored with the idea of "alternating current", AC for short. In alternating current, the voltage and the current oscillated, positive and then negative and then positive again, 60 times every second. If one used AC instead of Edison's DC (for "direct current") then you could make use of a wonderful invention called the transformer. (The transformer was invented in 1860 by Antonio Pacinotti. Transformers used to generate extremely high voltages are often called "Tesla coils".) A transformer used the fact that a wire with current in it creates a magnetic field. If the current varies, then the magnetic field varies. A changing magnetic field will create a current in a second wire. The amazing part of all this is that the voltage in the second wire could be very different from the voltage in the first wire. What the transformer transforms is the voltage.

Start with low voltage AC, put it through a transformer, and what comes out is high voltage AC. The advantage of high voltage AC is that it carries power with very little electric current. That means that there is very little power loss in the wires, so the power can be sent for long distances using long wires. There would be no need to have electric generating plants in every neighborhood. When the electricity got close to a home, it could be transformed again, to convert the electricity to low voltage, which is less dangerous to use. A small transformer could be place on the top of the pole that supported the wires. (Most neighborhoods today have just these transformers on the pole tops. When they burn out or otherwise fail, the neighborhood is left without electricity, and the transformer must be replaced or repaired. PG&E usually does this within a few hours.)

AC turned out to have such an advantage (no neighborhood power plants) that it completely won out over Edison's DC. Tesla got the support of George Westinghouse, and their system turned into the one we use today. The voltage in our homes is only 110 volts AC. (Actually 110 is an average voltage; the voltage varies between about -150 volts and +150 volts.) The voltage changes from positive to negative and then back to positive 60 times per second, i.e. 60 Hertz, abbreviated 60 Hz. In Europe, they use the slower frequency of 50 Hz, which is why their lights and their televisions flicker. (Our eyes don't notice flickering if it is faster than about 55 Hz. I think the Europeans made a dumb mistake, all for the purpose of trying to be a little more metric than the US. For a while, they also tried 50 seconds to the minute, and 50 minutes to the hour, but they gave up -- people couldn't get used to it. But the 50 cycles per second remained.)

But Edison did not give up without a fight. He tried to convince the public that high voltage was too dangerous to use in cities. He did this with a series of demonstrations of the danger, in which he invited the public to watch as he used the Westinghouse/Tesla high voltage system to electrocute puppies and other small animals. Eventually he put on a demonstration using high voltage to kill a horse. Edison had also invented a motion picture camera, and so he was able to make a movie of the electrocution of an elephant. The movie still exists, It was posted on the site Edison electrocutes Elephant, but apparently that site has now been removed. I find the movie horrifying. The name of the elephant executed was "Topsy" and she was a "bad" elephant who had been condemned to die for having killed three men. Apparently the Society for Prevention of Cruelty to Animals approved of the execution, since they thought it would be inhumane to hang Topsy. See the Topsy page for the details. In an unrelated quote, Edison said, "Non-violence leads to the highest ethics, which is the goal of all evolution. Until we stop harming all other living beings, we are still savages."

The ultimate horror, of course, was to show that high voltage electricity could kill humans. To do this, Edison convinced the State of New York to switch from hanging its condemned inmates, to electrocuting them. He also argued that this method of execution was more humane -- a conclusion that most modern observers think is exactly backwards. But New York adopted the method, and then so did several other states. Despite the publicity created by all these things, the advantages of AC won the day, and that is what we use now.

Quick review

Electricity is the flow of electrons, or other similar particles that carry "electric charge." By convention, the electric charge on the electron is -1.6×10^{-19} Coulombs. The proton has an equal and opposite charge. This is a basic quantum of charge; all observed charges are multiples of this, with the exception of the quark (hidden inside the nucleus) which has 1/3 or 2/3 of this value. Atoms usually have zero net charge, since the electrons and protons balance. (If they don't, the object is called an "ion".) Flowing charges (usually electrons) is called electric current, and is measured in amperes. (One ampere is a Coulomb of charge every second.) Current usually flows in loops, since otherwise charge builds up and the resulting force slows the flow.

Current can flow in gases, in vacuum, and in metal. When electrons do this, they usually lose some energy, and that is called electric resistance R, measured in ohms. The power lost is given by $P = I^2R$. Insulators are materials that are poor conductors (high R). Superconductors, which require very low temperatures, have R = 0. "High temperature superconductors" require temperatures of 150K, equal to –189 F.

Voltage measures the energy of the electrons. Power is voltage x current. High voltage is not particularly dangerous unless the current is large enough to give high power.

Batteries are rated by amp-hours. That is actually the total charge they can deliver. Multiply the amp-hours by voltage, and you get the total energy available in watt-hours.

In our homes we use AC (rather than DC) because the voltage can be changed easily using transformers. High voltage (low current) is used to bring the electricity to our homes, but the voltage is lowered to make it safer before it comes in.

The equations for electric force look similar to those of gravity. There are two laws, one for charge and one for current. The force drops with the square of the distance, so things 10x further away have 100x less force. But there are differences. Two charges with the same sign repel, and with opposite signs attract. For electrons, the electric force is much greater than gravity. When the force is between currents, we call it magnetism. Permanent magnets arise when the flow of electric charge within a large number of atoms is all in the same direction. Permanent magnets are used in magnetic compasses. No magnetic monopoles have ever been found, but the search continues. Electromagnets are made by making currents flow, typically in loops. They are used in auto door locks, speakers, earphones. When done in a rotary design, it is called an electric motor. Strong permanent magnets (samarium cobalt) has made small earphones and motors possible. Iron, when placed in a magnetic field, strengthens the field, unless the iron is warmer than its Curie temperature. Some materials remain magnetized after being exposed to magnetic fields, and these are used for magnetic recording.

When a wire passes through a magnetic field, currents flow in the wire, and this is used for electric generators. If the current is used to make the magnetic field stronger, the generator is called a dynamo. Dynamos are used for the generation of commercial electric power. The core of the Earth has a natural dynamo, and that makes the Earth into a magnet. The magnetism of the Earth flips, on average, several times every million years. That discovery is very useful in geology for determining the age of rocks.

Transformers change voltage and current, while wasting very little power. A Tesla coil produces very high voltages.

Magnetic levitation uses repelling magnetic fields. These fields are sometimes generated by moving metal or by AC current. Rail guns can accelerate metal to high velocities more efficiently (with less wasted energy) than can rockets.

end of chapter

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discussion questions

1. Read the following passage, taken from Popular Science magazine in 1892, and see what sense you can make of it, given the modern understanding of electricity.

> "We know little as yet concerning the mighty agency of electricity. Substantialists" tell us it is a kind of matter. Others view it not as matter, but as a

form of energy. Others, again, reject both these views. One professor considers it "a form, or rather a mode of manifestation, of ether." Another professor demurs to the view of his colleague, but thinks that "nothing stands in the way of our calling electricity ether associated with matter, or bound ether." Higher authorities cannot even yet agree whether we have one electricity or two opposite electricities. The only way to tackle the difficulty is to persevere in experiment and observation. If we never learn what electricity is, if, like life or like matter, it should remain an unknown quantity, we shall assuredly discover more about its attributes and its functions.

"The light which the study of electricity throws on a variety of chemical phenomenon cannot be overlooked. The old electrochemical theory of Berzelius is superseded by a new and wider theory. The facts of electrolysis are by no means either completely detected or coordinated. They point to the great probability that electricity is atomic, that an electrical atom is as definite a quantity as a chemical atom. The electrical attraction between two chemical atoms being a trillion times greater than gravitational attraction is probably the force with which chemistry is most deeply concerned."

from Popular Science, February 1892
(quoted in the Feb 1992 edition)

2. Discuss superconductivity. What is its value, and what are its limitations? How might it prove important in the future?

3. Why do we use AC in our homes? Would there be some advantages to using DC? Do you think we might change someday?

short questions

1. A Tesla coil is a kind of
   ( ) electric generator
   ( ) electric motor
   ( ) magnetic motor
   ( ) transformer

2. Samarium cobalt is a material that
   ( ) is used for strong magnets
   ( ) is repelled by magnets
   ( ) is superconducting at room temperatures
   ( ) created in a spark

3. The Earth's magnetism is created by
   ( ) buried loadstones
   ( ) the effect of the North Star
   ( ) currents in the atmosphere

( ) flow of liquid iron

4. High voltage is used for power transmission because
   - ( ) it travels faster
   - ( ) it is less likely to spark
   - ( ) it means the current is lower
   - ( ) it turns more power into heat

5. High temperature superconductors can operate at temperatures as high as
   - ( ) 4 K
   - ( ) 150 K
   - ( ) 273 K
   - ( ) 6000 K

6. Superconductors are
   - ( ) attracted to magnets
   - ( ) repelled to magnets
   - ( ) attracted or repelled (at different ends)
   - ( ) neither attracted nor repelled

7. The current in a flashlight bulb, compared to a 100 Watt lamp, is
   - ( ) much less
   - ( ) about the same
   - ( ) much more

8. The voltage of a flashlight battery is approximately
   - ( ) 1.5 volts AC
   - ( ) 1.5 volts DC
   - ( ) 110 volts AC
   - ( ) 110 volts DC

9. Helium is an important resource for
   - ( ) superconductors
   - ( ) transformers
   - ( ) generators
   - ( ) dynamos

10. The age of some rocks can be determined with the help of
    - ( ) their electric charge
    - ( ) their electric current
    - ( ) their electric resistance
    - ( ) their magnetism

11. The force of electric motors comes from
    - ( ) magnetic forces of currents
    - ( ) electric forces of charges
    - ( ) gravitational forces of currents

( ) dynamoic

12. AC is used instead of DC because
    ( ) it is safer
    ( ) it carries more power
    ( ) it allows use of transformers
    ( ) it is lower voltage

13. A magnetic monopole
    ( ) is an electron without charge
    ( ) is a proton without a charge
    ( ) is found in all permanent magnets
    ( ) doesn’t exist, as far as we know

14. A loadstone is
    ( ) a natural permanent magnet
    ( ) a natural electromagnet
    ( ) a rock found near the center of the Earth
    ( ) one of the first superconductors known